

Supporting Information Appendix

Transition to farming more likely for small, conservative groups with property rights, but increased productivity is not essential

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Table of Contents

S1. Outcomes of interactions	2
S2. Problems whilst translating Bowles and Choi's algorithm	2
S3. Robustness tests by Bowles and Choi.....	4
S4. The criteria for ranking.....	5
S5. Top simulations	6
S6. Statistical tests and correlations	9
S7. Justifying limit assumptions.....	10
S8. Group size and bourgeois-civic interactions.....	11
References	12

List of Tables

- Table S1. Outcomes of interactions in the Bowles and Choi (1) model.
Table S2. Bowles and Choi's robustness checks.
Table S3. Statistical outcomes of comparing prior and posterior distributions.
Table S4. Correlations between parameters.

List of Figures

- Figure S1. Justification for using the number of farmers at 9000 yBP in the ranking criteria.
Figure S2. Justification for using the number of farmers instead of number of bourgeois farmers in the ranking criteria.
Figure S3. Number of farmers for all simulations in rank order.
Figure S4. Scatter of parameters and number of farmers for top slices of simulations.
Figure S5. Scatter of parameters and number of farmers for all simulations.
Figure S6. The number of farmers and behavioral experimentation for different numbers of groups.
Figure S7. How the ratio of farming to foraging productivity, rather than absolute values, is important.
Figure S8. How f changes with group size and civic frequency.

S1. Outcomes of interactions

Table S1 Interactions in the Bowles and Choi (1) model. Outcomes of a game over the row player's product, when the row player is a forager (red) or a farmer (blue). Outcomes that are independent of the row player's technology strategy are shown in black.

	Bourgeois	Sharer	Civic
Bourgeois forager	Column player will take all row's product with probability 0.5	Row player keeps all of their product	Civics will take all of row's product with probability f
Bourgeois farmer	Row player keeps all of their product		
Sharer forager	Column player will take all of row's product	Row's product will be shared equally	Row's product will be shared equally
Sharer farmer	Row's product will be shared equally		
Civic forager	Column player will take all of row's product with probability $(1-f)$, otherwise row player's product will be shared equally with all the civics in the group	Row's product will be shared equally	Row's product will be shared equally
Civic farmer	Row's product will be shared equally		

S2. Problems whilst translating Bowles and Choi's algorithm

Whilst translating the published description of Bowles and Choi's (1) algorithm into code we spotted several mistakes and misleading or unclear explanations. Bowles and Choi clarified these over email and the corrections/explanations are as follows:

1. In a Bourgeois - Bourgeois interaction one will win with probability of 0.5.
2. $\theta = -(0.45 - w)/5$.
3. Payoffs are reset to zero after each iteration.
4. One iteration = one generation = 20 years.

5. The benchmark parameters for v and γ are 8 and 5 respectively.
6. “ π^S be the average payoff of the group” on page 11 of the supplementary material should be a $\bar{\pi}$.
7. π_i is the average payoff of group i .
8. If the cultural model is chosen to be a sharer (for example), then one sharer will be chosen at random from the cultural model group.
9. An agent could pick itself as its own cultural model.
10. The reward or cost when a civic attempts to punish another individual is shared between all the civics in the group.
11. In the equation for f , n is the size of the group, hence $(1 - \alpha - \beta)n$ is the number of civics in the group.
12. A farmer is picked as a cultural model with probability (frequency of farmers) n /(freq. of farmers n +freq. of foragers n), and similarly for foragers.
13. The number of agents which immigrate into a group is equal to the number that migrate from the group.
14. All the groups are paired for between-group interactions.
15. Any value of θ greater than 1.5 is set to 1.5 (although this has no effect when the benchmark parameters are used).
16. It is not the case that updating will definitely occur if the model’s fitness is greater than the updating individual’s. What actually happens is the following:

if *the model’s fitness > the updating individual’s* **then**

$x = \text{model’s fitness} - \text{updating individual’s fitness}$;

if $x < \text{a random number between 0 and 1}$ **then**

the individual will update it’s strategy to the model’s strategy;

else

the individual will not update it’s strategy;

end

end
17. The same set of random numbers are used for each run of 1000 simulations, each of the 1000 simulations have different results though.

S3. Robustness tests by Bowles and Choi.

Bowles and Choi (1) did several robustness tests (see section 10 of their supplementary material). Table S2 shows the parameters that they varied and the values that they changed each of them to one-by-one. It also shows whether the number of majority bourgeois farmer simulations generally increased or decreased as the parameter was increased through the values given.

Table S2 Parameters varied by Bowles and Choi, and the values used. The default values are shown in bold. The result of whether the amount of bourgeois farmer majority simulations increases or decreases when these variations are applied is also noted.

Parameter	Variations	Result
The productivity of the farmers investment, r	1.4, 1.5 , 1.53, 1.57*	Increase**
Migration rate, m	0.18, 0.2 , 0.22, 0.25	Increase
Cost of losing a conflict, C	1.25, 1.5 , 1.75	Increase
Contestability of a hunter-gathered product, μ_h	0.7, 0.8, 0.9, 1	Decrease
Contestability of a farmed product, μ_a	0 , 0.05, 0.1, 0.15	Decrease
Resource transfer amount, τ	1, 2, 3	Decrease
Probability of a between-group conflict, κ	0.33, 0.5, 1	Decrease
Behavioral experimentation, ϵ	0.24, 0.25 , 0.26	Increase

* r is varied to 1.57 in the Holocene, but kept as 1.5 in the Pleistocene for this change.

** Increase when r is varied through 1.4, 1.5 and 1.53.

S4. The criteria for ranking

We have decided to use the number of farmers at 9,000 yBP as our measure of how good a simulation is. Alternatively, we could have looked at how much farming existed over the period of agricultural establishment to present day, as perhaps simulations which have many farmers at 9000 yBP, but then decrease in number should not be classified as simulations reflecting reality. However, we find a mostly equal trend between the number of farmers at 9000 yBP and the number at 0 yBP, between the number of farmers at 9000 yBP and the minimum number of farmers between 0 and 9000 yBP, and also between the number of farmers at 9000 yBP and the average number of farmers between 0 and 9000 yBP (figure S1). Hence, we concluded that it is realistic to assume that a simulation will have a similar number of farmers between 0 and 9000 yBP.

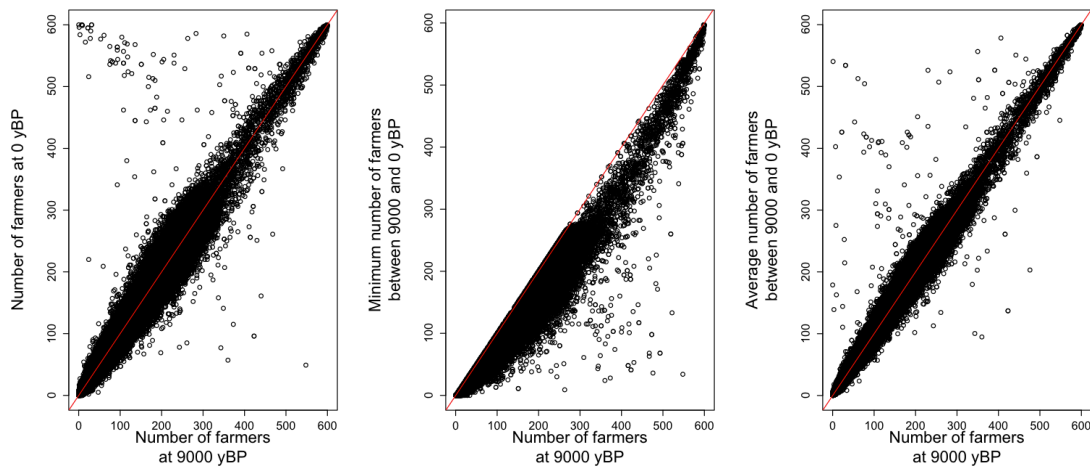


Figure S1 How the number of farmers at 9000 yBP in the model relates to the number at 0 yBP (left); the minimum number between 9000 and 0 yBP (middle); and the average number between 9000 and 0 yBP (right). The line $y = x$ is shown in red.

Using the number of bourgeois farmers vs. the number of farmers as our acceptance criteria makes little difference to the results. We found that out of all our simulations 92.5% were in both the highest 1% number of farmers and the highest 1% number of Bourgeois farmers. We can see the small difference this makes to the outcomes in figure S2.

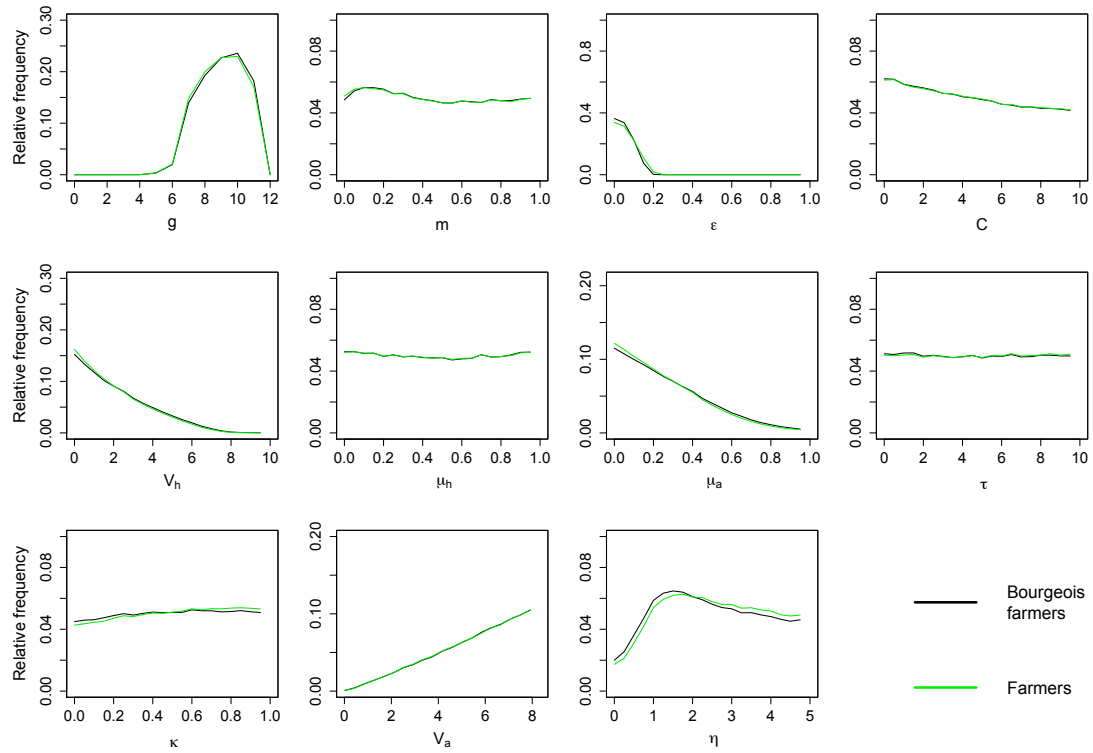


Figure S2 Relative frequency plots of each parameter for the top 1% slices of the 1.2×10^7 simulations. When the number of Bourgeois farmers is used as the success criteria (black) and when the number of farmers is used as the success criteria (green).

S5. Top simulations

Of all the simulations, there are only a few (~13%) that have a majority of farmers at 9000 yBP, and only around 1% which have more than 500 farmers at 9000 yBP – these are the “top” simulations. Figure S3 shows the trend when ranking the simulations on how many farmers they have at 9000 yBP. Figure S4 shows the trends in the parameter values in different top slices of the simulations, and figure S5 shows these trends for all the simulations.

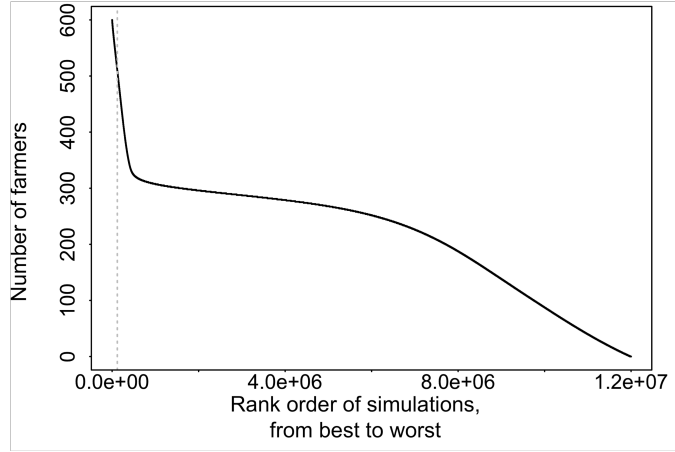


Figure S3 The number of farmers in the 9,000 yBP iteration of each of the 1.2×10^7 simulations. In rank order from the largest (best) to the smallest (worst) number of farmers. The top 1% of simulations are to the left the dashed line.

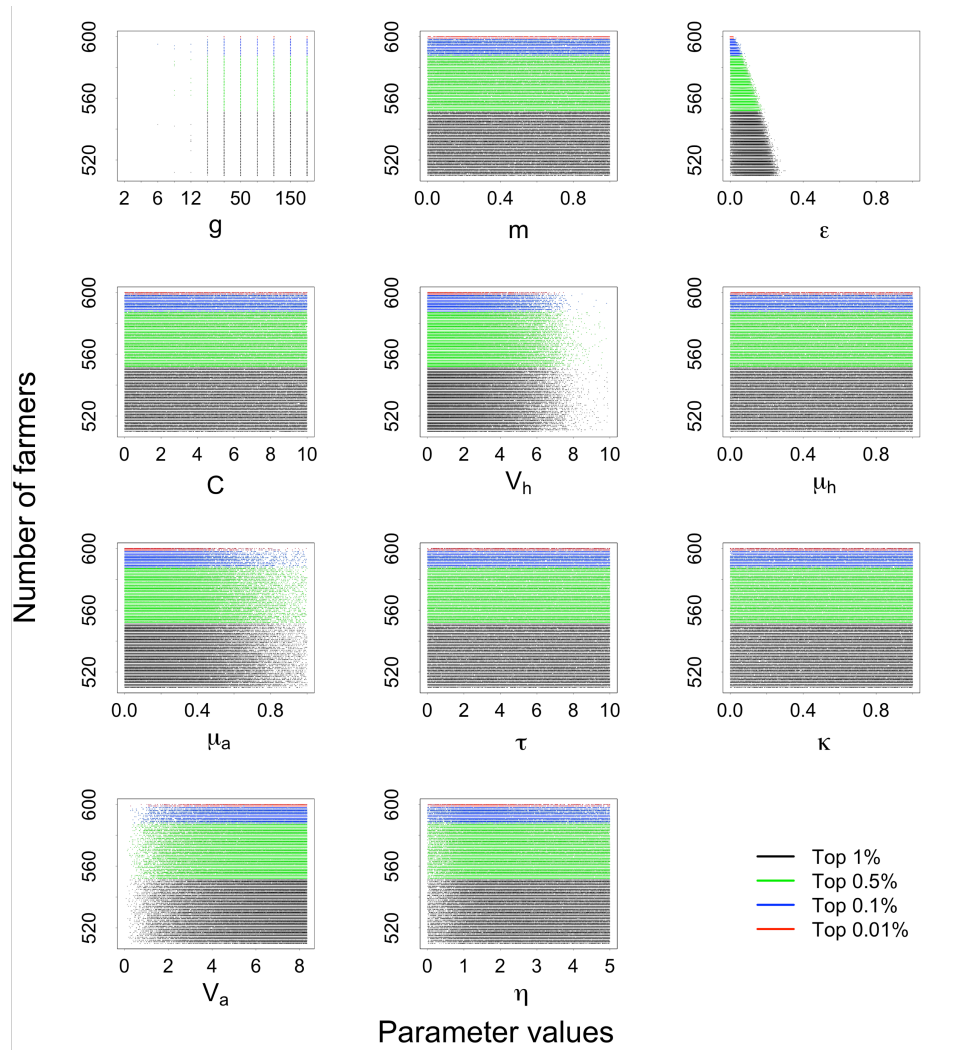


Figure S4 The number of farmers and each parameter value for the top 1% (all points), top 0.5% (red, blue and green points), top 0.1% (red and blue points) and top 0.05% (red points) of simulations.

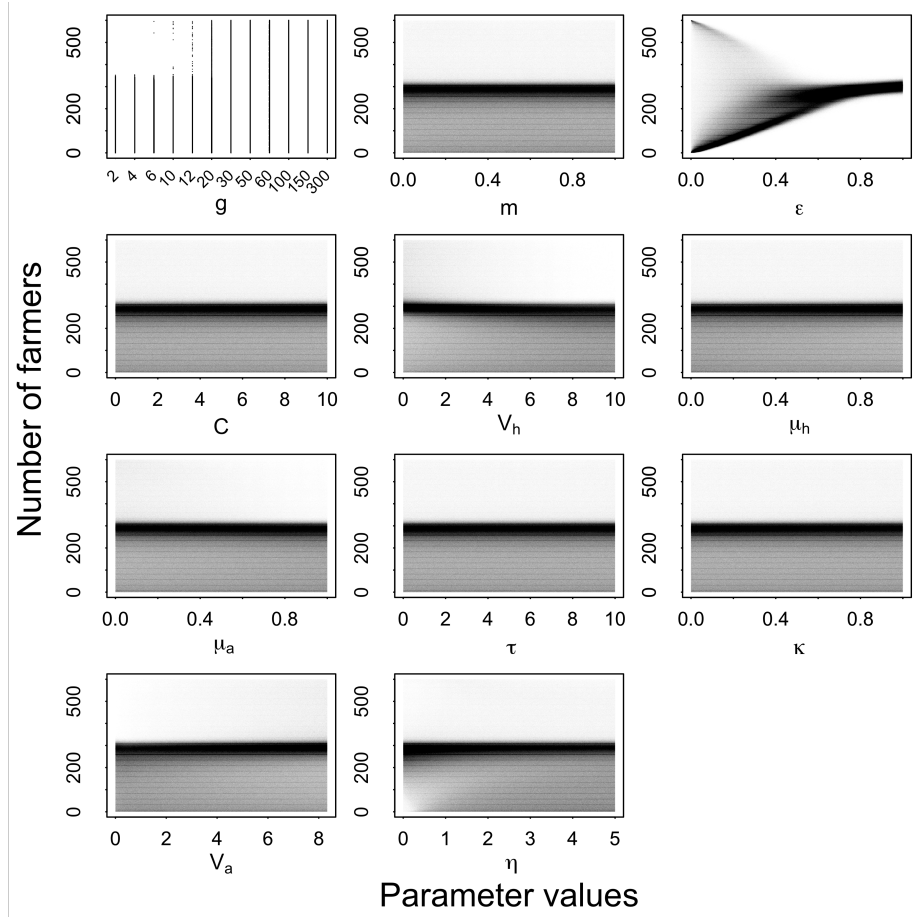


Figure S5 The number of farmers and each parameter value for all 1.2×10^7 simulations (each point represents one simulation). Correlation coefficients between parameter values and the number of farmers are given in table 2 of the main text.

S6. Statistical tests and correlations

We statistically tested whether our top 1% distributions were significantly different from our prior distributions (all the simulations) for each parameter (table S3); whether each parameter value was correlated with the number of farmers for a range of different top slices (table 2 of the main text); and whether any two parameters were significantly correlated in the top 1% of simulations (table S4) – those with a Spearman’s rank correlation coefficient greater than 0.1 are plotted in figure 3. Figure S6 shows the relationship between the two strongly correlated parameters, number of groups (g) and behavioral experimentation (ε).

Table S3 Statistics from a two-sample Kolmogorov-Smirnov test and a Chi-squared test between the prior (all 1.2×10^7 simulations) and posterior (top 1% of simulations) distributions for each parameter.

	g	m	ε	C	V_h	μ_h	μ_a	τ	κ	V_a	η
D	0.559	0.028	0.781	0.054	0.421	0.008	0.337	0.005	0.031	0.280	0.088
χ^2	159439	489	511448	1833	116176	101	68993	26	613	49264	7453

Table S4 Spearman’s rank correlation coefficients between all pairs of parameters in the top 1% of the 1.2×10^7 simulations. The highest correlation coefficients (where $|\rho| \geq 0.1$) are highlighted in orange.

[illegible]

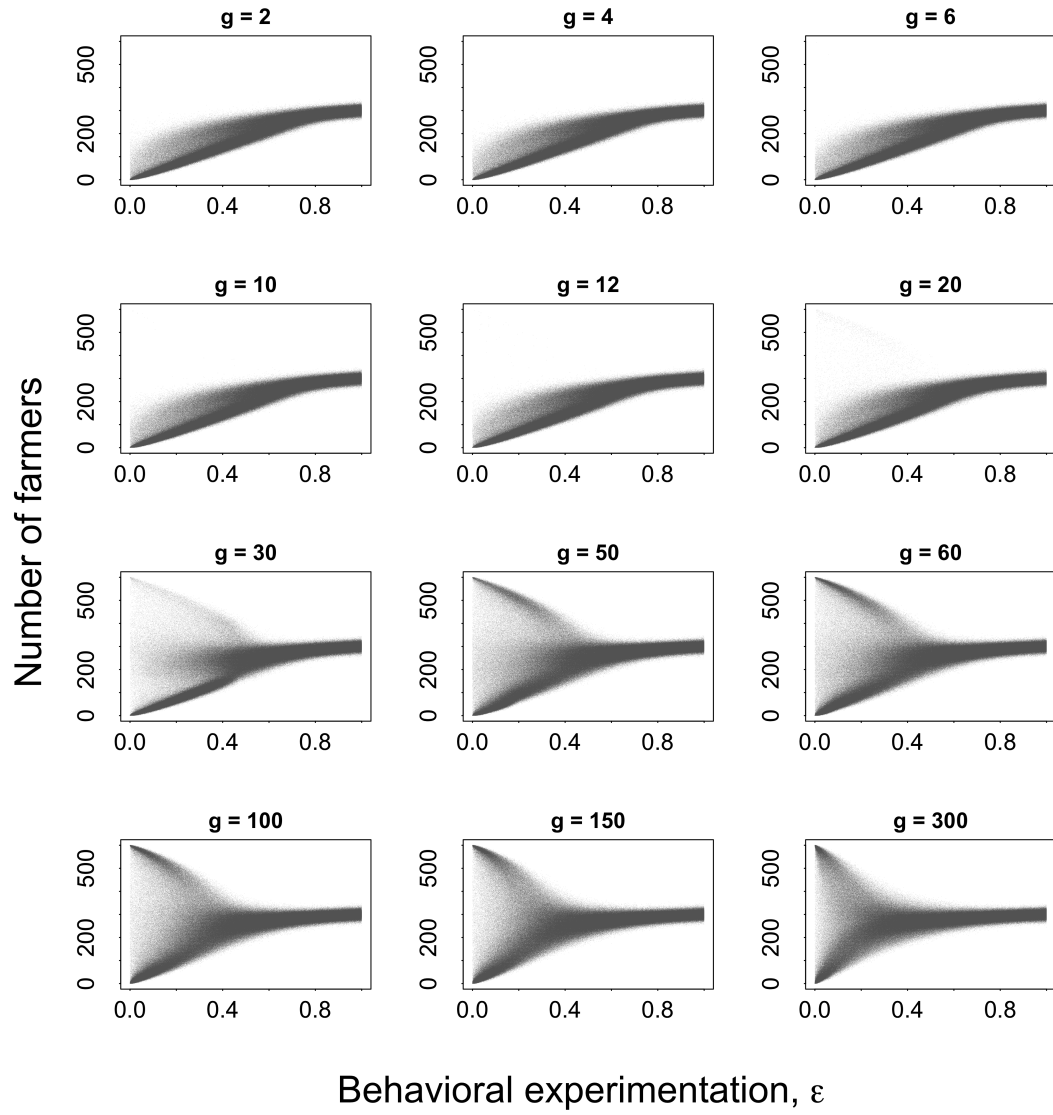


Figure S6 The number of farmers and the innovation rate/ behavioral experimentation (ϵ) for different number of groups (g), using all 1.2×10^7 simulations (each point represents one simulation).

S7. Justifying limit assumptions

Finding the maximum value for the payoff parameters (C , V_h , τ and z) involved assumptions that were not grounded in observed data. However, we have seen in the main analysis that C and τ are relatively insensitive in this model, so perhaps increasing the upper limit of their range would make no difference.

Figure S7 shows a comparison of the posterior distributions when we half the range for V_h and for z to that of their original ranges. We can see that the distributions (other than for V_h and z) are very similar, which suggests that the ratio of V_a to V_h , rather than the individual values for V_h and z , is key. Hence, it is really only the value of this ratio that has an effect on the number of farmers in this model, so increasing the upper limit for this should make no difference to our interpretation either.

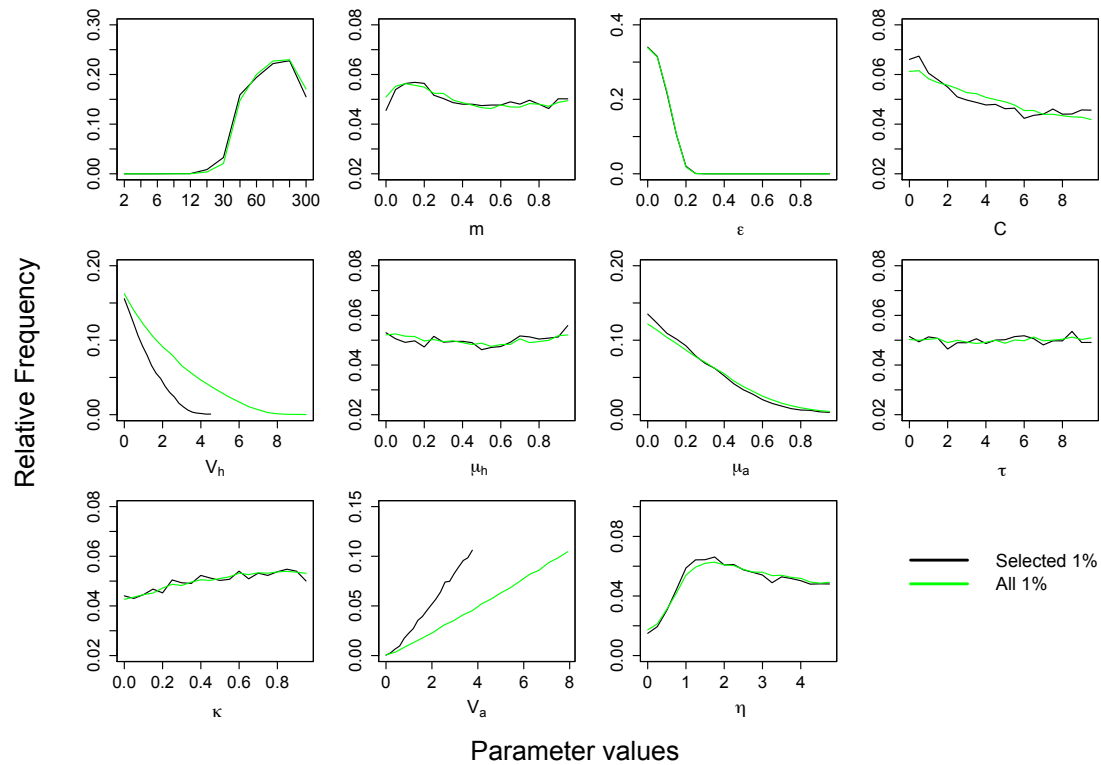


Figure S7 Relative frequency plots of each parameter for the top 1% of simulations (green) and simulations in the top 1% which had both $V_h \leq 5$ and $z \leq 9.605$ (black).

S8. Group size and bourgeois-civic interactions

The probability of a civic winning in a bourgeois-civic interaction (f) changes with different group sizes. In some circumstances it is almost impossible for a bourgeois to win, and in others it is impossible for the civic to win. This relationship can be seen in figure S8.

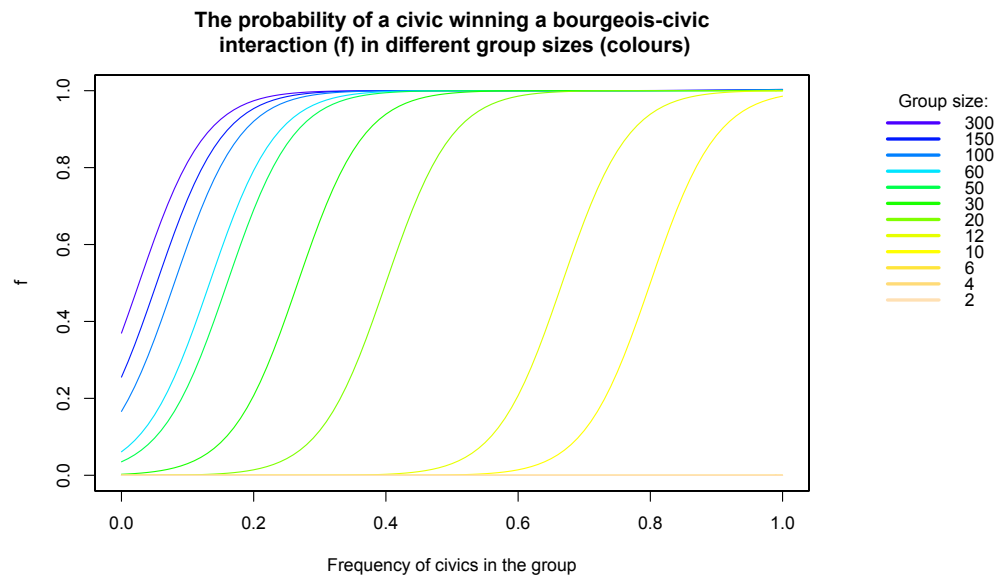


Figure S8 The probability of a civic winning a bourgeois-civic interaction when group size and frequency of civics are varied.

References

- (1) Bowles S, Choi J-K (2013) Coevolution of farming and private property during the early Holocene. *Proc Natl Acad Sci USA* 110(22):8830-8835.